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B Hadron Production and $b\bar{b}$ Correlations at CDF

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B HADRON PRODUCTION AND $b\bar{b}$ CORRELATIONS AT CDF

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We report on measurements of B differential cross sections and correlated $b\bar{b}$ cross sections in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV with the Collider Detector at Fermilab (CDF). We have also measured the ratios of the branching fractions of B mesons decaying to a J/ψ and a light meson and b quark fragmentation fractions. The Λ_b baryon production has been observed using the decays $\Lambda_b \rightarrow \Lambda_c^+ e^- \bar{\nu}_e X$ and $\Lambda_b \rightarrow J/\psi\Lambda$.

1 Introduction

Production of b quarks in $p\bar{p}$ collisions constitutes a benchmark process for the study of perturbative QCD. In high energy $p\bar{p}$ collisions, the strong coupling constant, α_s, becomes small enough for b quark production at sufficiently high momentum transfer that perturbative QCD is expected to provide reliable predictions. The cross section for heavy quark production has been theoretically calculated up to the order of α_s^3. Measurements of b quark cross sections at the Tevatron ($\sqrt{s}$ = 1.8 TeV) show consistently higher values than the theoretical prediction. Several independent measurements can be made to understand this normalization difference. A useful approach is to measure the cross section for different regions of phase space (differential cross section) and compare it with the NLO QCD. We can also investigate production correlations between the two b quarks by measuring $b\bar{b}$ cross section, which gives further information on the underlying QCD production mechanisms.

Bottom quarks produced in $p\bar{p}$ collisions hadronize to B hadrons, bound states of quarks including a b quark. The fragmentation fractions of a b quark into the B hadrons have been not directly measured in a hadron collider in spite of their importance in B studies. Experimental studies of the B hadron decays provide an opportunity to understand the behavior of the interactions between the quarks at short distance scales. In the CDF experiment, a significant number of B hadrons decaying semileptonically or hadronically have been observed for B^+, B^0, B_s^0, and Λ_b states, which allows to study the relative production rate of the B mesons and the branching fractions.

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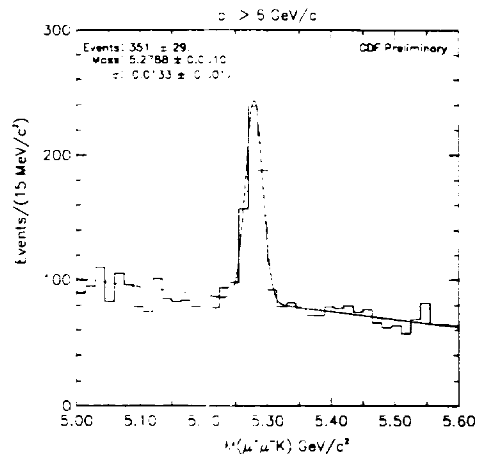

Figure 1: $J/\psi K$ invariant mass for $P_T^B \geq 6$ GeV/c.

2 B Meson Differential Cross Section

The first direct measurement of the B meson differential cross section, $d\sigma/dP_T$, for the exclusive decays $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ based on 19.3 pb^{-1} of data from the 1992-1993 run (Run 1A) has been published previously [1]. The cross sections were found to be higher than the NLO QCD prediction by a factor of 1.9 ± 0.3 while the shape of the cross section reasonably agrees with the theory. Here we extend the analysis using more data taken during the 1993-1996 run (Run 1B), representing an integrated luminosity of 54.4 pb^{-1}. In this talk, we present the result for the decay $B^+ \to J/\psi K^+$ only. The analysis using the decay $B^0 \to J/\psi K^{*0}$ is in progress.

The selection of B candidates starts with reconstructing a J/ψ with a muon pair. We require the transverse momentum (P_T) to be greater than 2 GeV/c for both muons and the dimuon invariant mass to be less than 3σ from the J/ψ mass. The K candidates are required to have $P_T \geq 1.25$ GeV/c. The proper decay length of a B candidate, $c\tau \equiv L_{xy}^B m_B / P_T^B$, can be calculated using the transverse projection of the B vertex displacement (L_{xy}^B) and the B transverse momentum (P_T^B). The background from a prompt J/ψ and a

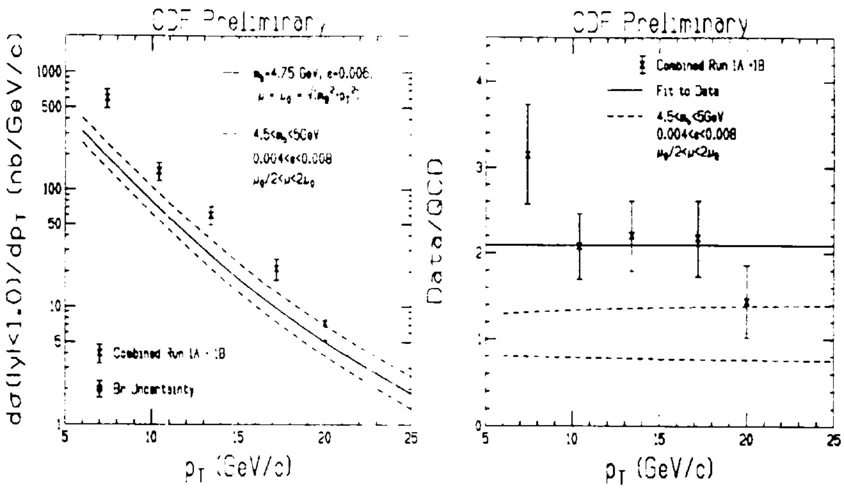

Figure 2: B differential cross section compared to the NLO QCD prediction.

particle from the primary vertex is significantly reduced by requiring $c\tau$ to be greater than 100 μm. The resulting invariant mass distribution of a J/ψ candidate and a kaon candidate is shown in Figure 1.

The B meson differential cross section, $d\sigma/P_T$, is calculated as follows.

$$\frac{d\sigma}{dP_T} = \frac{N_B}{2 \cdot \int dt\mathcal{L} \cdot A \cdot e \cdot Br(B \rightarrow J/\psi K) \cdot Br(J/\psi \rightarrow \mu^+\mu^-) \cdot \Delta P_T} \qquad (1)$$

where N_B is the number of B mesons, $\int dt\mathcal{L}$ is the integrated luminosity, A is the detector acceptance, e is the detector efficiency, and ΔP_T is the width of the P_T bin. The combined branching ratio [2], $(6.55 \pm 1.01) \times 10^{-5}$, is used for the $B^+ \rightarrow J/\psi K^+$ and $J/\psi \rightarrow \mu^+\mu^-$ decays. A Monte Carlo based on the NLO QCD is employed to estimate the acceptance for each P_T bin. In the Monte Carlo, we use the MRSD0 structure functions [3], the normalization scale $\mu = \sqrt{P_T^2 + m_b^2}$ where b quark mass, m_b, is set to be 4.75 GeV/c^2, the Peterson fragmentation parameterization [4] with a fragmentation parameter (ϵ) of 0.006 [5]. The efficiency for the B mesons is measured using inclusive J/ψ data and the full detector simulation.

We combine the Run 1A and Run 1B results by weighting each set of measurements by their respective statistical errors. Figure 2 shows the combined cross sections. The cross sections are plotted at the mean P_T value of the data points. The solid curve shows the NLO QCD prediction and the dashed curves indicate the change in the theoretical prediction, associated with uncertainty in the b quark mass, the renormalization scale, and the fragmentation parameter. We also plot the ratio of the data and the NLO QCD prediction in Figure 2. The shape of the cross section is found to be consistent with the theoretical prediction within the uncertainties. A fit to data yields an overall scale factor of 2.1 ± 0.2, consistent with the Run 1A result.

3 $b\bar{b}$ Correlated Cross Section

The production of $b\bar{b}$ pairs in $p\bar{p}$ collisions is studied using high mass dimuon data ($M_{\mu\mu} \geq 5$ GeV/c^2) from the 1992-1993 run. Dimuon events result from decays of $b\bar{b}$ and $c\bar{c}$, the Drell-Yan process, Υ decays, and decays of π or K mesons. For the separation of $b\bar{b}$ events from others, we make use of the precision tracking provided by the CDF silicon vertex detector. Specifically, the impact parameter of a muon is used to determine the $b\bar{b}$ content of the dimuon data. The impact parameter is defined as the distance of closest approach to the primary vertex in the transverse plane. The impact parameter distribution for particles from decays of long lived B hadrons shows broader spectra than those from prompt decays or charm decays, which allows the fraction of $b\bar{b}$ events to be determined by the fit in the impact parameter space. Since there are two muons in an event, a fit is performed in the two dimensional impact parameter space where each axis represents the impact parameter of one of the two muons. We use a binned log likelihood method in the fit. The likelihood function consists of four main components - $b\bar{b}$ events, $c\bar{c}$ events, prompt dimuon events, events with a muon from bottom decay and a muon from prompt decay. Prompt dimuon events include those from the Drell-Yan process and Υ decays. Muons from decays of a pion or a kaon are also regarded as prompt muons since the CDF track reconstruction algorithm removes decay muons with a discernible kink. The impact parameter distributions for $c\bar{c}$ events and events with a bottom muon and a prompt muon is found to be very similar to each other so that a linear combination of these two components is used in the fit. Figure 3a shows the projections of the two dimensional distributions from the data and the contributions of each component obtained from the fit. The $b\bar{b}$ cross section is obtained by dividing the number of $b\bar{b}$ events by the acceptance, the detector efficiency, the branching fraction [2] for the dual semileptonic decay of a $b\bar{b}$ pair, $(1.06 \pm 0.10) \times 10^{-4}$, and the integrated luminosity $\int dt\mathcal{L}$ (17.4 pb^{-1} from Run 1A). The muon efficiencies are measured using muons from J/ψ decays. The acceptance is determined using a $b\bar{b}$ Monte Carlo generator based on the NLO QCD calculations and the CLEO Monte Carlo program [6] for b decays. For the measurement of $b\bar{b}$ cross sections

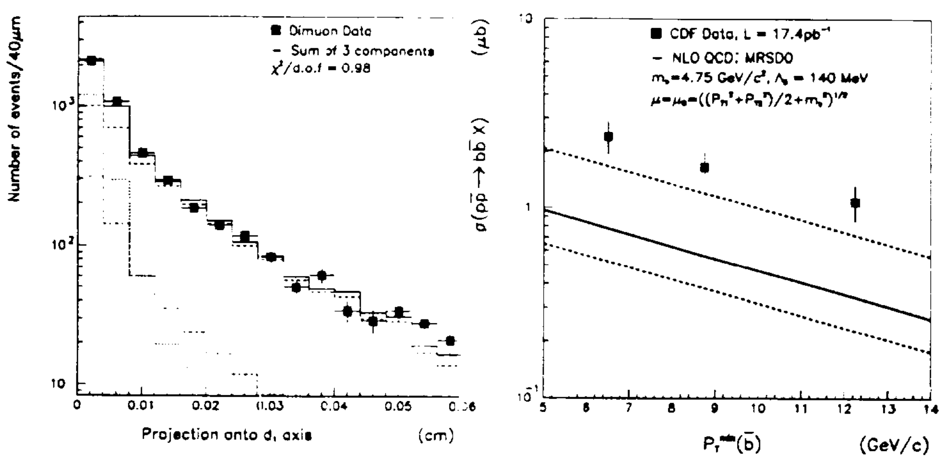

Figure 3: **a)** Comparison between the projections of the data distribution and a sum of the 3 components. The contribution of $b\bar{b}$ events is denoted by dashed line, that of prompt dimuons by dotted line, and that of $c\bar{c}$ events and events with a b muon and a prompt muon by dash-dotted line. b) $\sigma(P_T(b) \geq 6.5$ GeV/c, $P_T(\bar{b}) \geq P_T^{min}$, $|y_b, y_{\bar{b}}| \leq 1)$.

with different P_T thresholds, we use three different data samples corresponding to three different intervals in P_T of $\bar{b}$ quark: 3-5, 5-7, and $\geq$ 7 GeV/c. The P_T threshold of $\bar{b}$ quark, P_T^{min}, is chosen such that 90% of muons satisfying the above P_T thresholds come from bottom decays with $P_T(\bar{b}) \geq P_T^{min}$. The measurements of the $b\bar{b}$ cross section are shown in Figure 3b. The uncertainty of the theoretical prediction (dashed line) is obtained by varying the QCD parameters within the range of acceptable values. The data is systematically higher than the QCD calculations. The variation of the cross section with different P_T thresholds is consistent with the theoretical prediction.

We have also investigated correlations between the two muons from $b\bar{b}$ decays. The geometrical correlations is studied by examining the opening angle between the muons in the transverse plane. The two dimensional impact parameter fit is performed in each $\delta\phi$ bin to obtain the number of $b\bar{b}$ events.

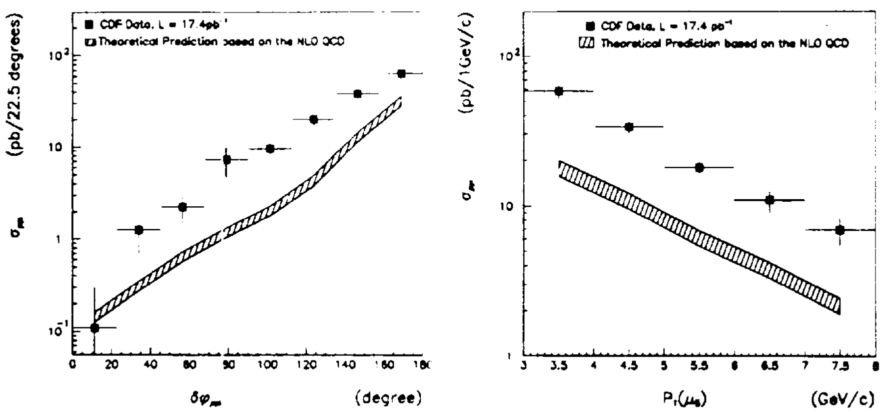

Figure 4: (a) Opening angle distribution between the two muons from $b\bar{b}$ decays for $P_T(\mu_b), P_T(\mu_{\bar{b}}) \geq 3$ GeV/c. (b) $P_T(\mu_b)$ distribution for $P_T(\mu_b) \geq 3$ GeV/c.

For the study of kinematic correlations, $P_T(\mu_{\bar{b}})$ distribution with $P_T(\mu_b) \geq 3$ GeV/c is obtained using the impact parameter fit for each $P_T(\mu_{\bar{b}})$ bin. The results are shown in Figure 5 and are compared to the prediction based on the NLO QCD calculations. The shape of $P_T(\mu_{\bar{b}})$ and the opening angle distributions are adequately described by the theoretical prediction.

4 Bottom Meson Branching Fractions Involving J/ψ Mesons

The exclusive B decays involving a J/ψ meson have been observed and discussed in several CDF papers. In this analysis, we measure the ratio of the branching fractions of these decay modes and the fragmentation fractions for B mesons. The decay modes used are $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^0_S$, $B^+ \to J/\psi K^*(892)^+$, $B^0 \to J/\psi K^*(892)^0$, and $B^0_s \to J/\psi \phi(1020)$.

We reconstruct a $J/\psi \to \mu^+\mu^-$ candidate by requiring the lowest and highest muon P_T to be greater than 1.8 and 2.5 GeV/c, respectively. For the $B^+ \to J/\psi K^+$ decay, we require $P_T(K^+) \geq 1.5$ GeV/c and the resulting B

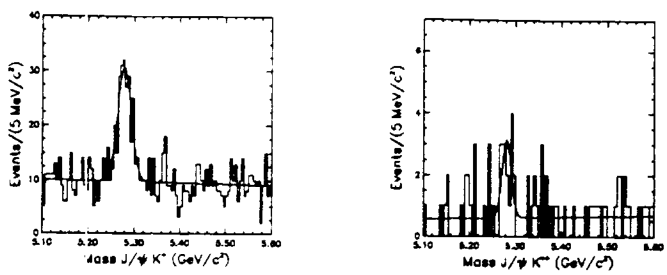

Figure 5: Invariant mass spectra for B^+ mesons.

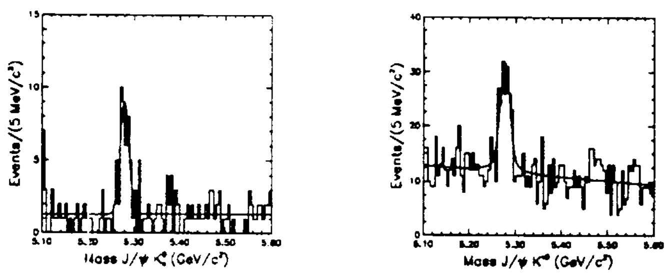

Figure 6: Invariant mass spectra for B^0 mesons.

candidate to have $P_T \geq 8$ GeV/c. We also require the proper decay length of a B candidate (defined in section 2) to be positive in order to reduce the backgrounds from prompt J/ψ production. The reconstruction of the four other decay modes are performed with similar cuts on the strange mesons. The invariant mass distributions of the reconstructed B mesons are shown in Figures 5, 6, and 7. We use a 19.6 pb^{-1} of data from the 1992-1993 run. The numbers of the reconstructed B mesons are found to be 154 ± 19 for $B^+ \rightarrow J/\psi K^+$, 36.9 ± 7.3 for $B^0 \rightarrow J/\psi K_s^0$, 12.9 ± 4.3 for $B^+ \rightarrow J/\psi K^{*+}$, 95.4 ± 14.3 for $B^0 \rightarrow J/\psi K^{*0}$, and 29.4 ± 6.2 for $B^0 \rightarrow J/\psi\phi$. The number of the observed B^+ mesons, N_B, for the $B^+ \rightarrow J/\psi K^+$ decay can be written as follows.

$$N_{B^+} = \sigma(p\bar{p} \rightarrow \bar{b}) \cdot f_u \cdot Br(B^+ \rightarrow J/\psi K^+) \cdot Br(J/\psi \rightarrow \mu^+\mu^-) \cdot A \cdot e \quad (2)$$

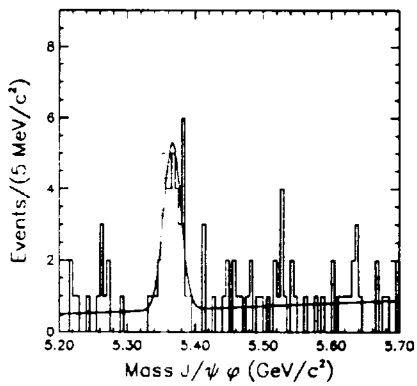

Figure 7: Invariant mass spectra for B_s^0 mesons.

where f_u is the fragmentation fraction into a B^+ meson, A is the acceptance and e is the detector efficiency. The cross section for b production, the branching fraction for $J/\psi \rightarrow \mu^+\mu^-$, and the muon acceptance and efficiency are common factors in the expressions for the other decay modes. The acceptance and efficiency for a strange meson are determined with a Monte Carlo method employing the full CDF detector simulation. By taking ratios of the number of the observed events for the decay modes, we obtain the ratios of the product of the branching fractions and the fragmentation fractions.

Assuming that $f_u = f_d$ and $f_s = (0.40 \pm 0.06) f_u$[9,10], we extract the branching fraction of the $B_s^0 \rightarrow J/\psi\phi$ decay using the ratios between the number of the B_s^0 mesons and the other B mesons and the world averaged values of the branching fractions for the other four decay modes. Using this method, we obtain the branching fractions as follows

$$Br(B^+ \rightarrow J/\psi K^+) = (0.82 \pm 0.18 \pm 0.07) \times 10^{-3} \qquad (3)$$

$$Br(B^0 \rightarrow J/\psi K_s^0) = (1.14 \pm 0.27 \pm 0.09) \times 10^{-3} \qquad (4)$$

$$Br(B^+ \rightarrow J/\psi K^{*+}) = (1.73 \pm 0.55 \pm 0.15) \times 10^{-3} \qquad (5)$$

$$Br(B^0 \rightarrow J/\psi K^{*0}) = (1.39 \pm 0.32 \pm 0.11) \times 10^{-3} \qquad (6)$$

$$Br(B_s^0 \rightarrow J/\psi\phi) = (0.93 \pm 0.28 \pm 0.17) \times 10^{-3} \qquad (7)$$

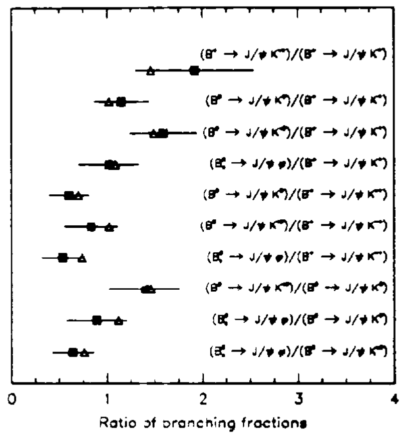

Figure 8: Ratio of branching fractions. The measurements are denoted by the filled box with a error bar and theoretical prediction by open triangles.

We have compared our measured ratios of the branching fractions with a calculation [11] of the decays of B mesons, using the factorization and heavy quark symmetries. The results are shown in Figure 8. The predictions agree very well with the observed values.

We also extract the fragmentation fractions for B mesons using the theoretically predicted ratios of the branching fractions [11] and an estimate for the fraction for Λ_b [12], $f_{\Lambda_b} = 0.096 \pm 0.017$. We determine that $f_u = 0.39 \pm 0.04 \pm 0.04$, $f_d = 0.38 \pm 0.04 \pm 0.04$, and $f_s = 0.13 \pm 0.03 \pm 0.01$, which implies the suppression of $s\bar{s}$ production relative to $u\bar{u}$ and $d\bar{d}$ production in a b quark fragmentation.

5 Λ_b Production

5.1 *Semileptonic Decay of* Λ_b

We report the observation of Λ_b baryons through the decay mode $\Lambda_b \rightarrow \Lambda_c^+ e^- \bar{\nu}_e X$ where $\Lambda_c \rightarrow pK^-\pi^+$. We use the data from the 1992-1993 run, corresponding to an integrated luminosity of 19 pb^{-1}.

The electrons are required to have $E_T \geq 9$ GeV. The main cuts used for

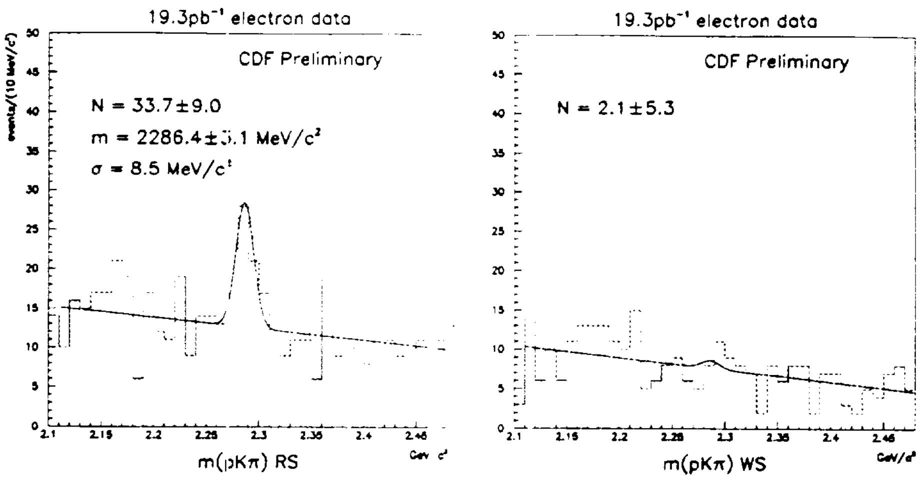

Figure 9: Invariant mass distribution of Λ_c candidates in the electron data.(**a**) Right-Sign (RS) combination (**b**) Wrong-Sign (WS) combination.

the reconstruction of Λ_c are the proton and kaon P_T cuts which are $P_T(p) \geq$ 2 GeV and $P_T(K) \geq 1$ GeV/c, respectively. For the signature for Λ_b baryons, we use charge correlation between the electron and the Λ_c baryon in a Λ_b decay. The right sign (RS) combination is for the Λ_c and the electron to have opposite charges. If the Λ_c and the electron have the same charge, they make a wrong-sign (WS) pair. Figure 9 shows the invariant mass distribution of Λ_c candidates for the right-sign (RS) and wrong-sign (WS) combinations. We observe 33.7 ± 9.0 events in the RS peak and no discernible WS peak. The backgrounds from *fake* electrons or *fake* Λ_c equally contribute to the RS and WS combinations. The lack of a WS peak indicates that these backgrounds do not contribute to the RS Λ_b signals. Other physics processes which may contribute to the RS peak are the decay $\bar{B}^0 \to e^- D^{*+} X$ where $D^{*+} \to D^0 \pi^+$ and $D^0 \to K^+ \pi^-$ and the decay $\bar{B} \to \Lambda_c^+ D_s^- X$ followed by $D_s^- \to e^- \bar{\nu}_e Y$. The contributions of these decay modes to the signal have been found to be negligible.

From the number of the observed Λ_b events, N_{Λ_b}, we determine the product of the fragmentation fraction f_{Λ_b} and the branching fraction $Br(\Lambda_b \to \Lambda_c^+ e^- \bar{\nu}_e X) Br(\Lambda_c \to p K^- \pi^+)$ as follows.

$$\sigma_b \cdot f_{\Lambda_b} \cdot Br = \frac{N_{\Lambda_b}}{2 \cdot \int dt\mathcal{L} \cdot A \cdot e} \tag{8}$$

where σ_b is the inclusive b cross section and all other notations are defined in the same way as in Sections 2 and 4. The acceptance A and the efficiency e are obtained using a Monte Carlo simulation. In the Monte Carlo simulation, an ISGW-based decay distribution is used for the Λ_b decay. Using the CDF measurement of the b cross section, $\sigma_b(P_T \geq 10.5$ GeV/c, $|y| \leq 1) = 1.99 \pm 0.30 \pm 0.38 \mu$b [1], we obtain $f_{\Lambda_b} Br(\Lambda_b \rightarrow \Lambda_c^+ e^- \bar{\nu}_e X) Br(\Lambda_c \rightarrow pK^-\pi^+) = (9.3 \pm 2.5^{+4.6}_{-4.0}) \times 10^{-4}$. The dominant systematic uncertainty comes from the Λ_b decay model. We obtain a variation of 25% when a V-A model is used instead.

5.2 *Exclusive Decay of* Λ_b

We present the measurement of the branching fraction of the decay $\Lambda_b \rightarrow J/\psi\Lambda$ using all the data taken from 1992 to 1996, representing an integrated luminosity of 115 pb^{-1}. In order to avoid additional uncertainties due to the b quark production and the detection efficiency, we study the relative production rate of the Λ_b baryon to the B^0 meson using the exclusive decays. The decay $B^0 \rightarrow J/\psi K^0_s$ is used for the comparison to the exclusive Λ_b decay.

The J/ψ candidates are selected by requiring both muons to have $P_T \geq 2$ GeV/c. The long lived Λ and K^0_s particles are identified by requiring the transverse decay length from the primary vertex to be greater than 1 cm. The proton and the pions in the decays $\Lambda \rightarrow p\pi$ and $K^0_s \rightarrow \pi^+\pi^-$ are required to have $P_T \geq 0.4$ GeV/c. The invariant mass distributions for the Λ_b and K^0_s candidates are shown in Figure 10. In the Figure, the left plots are obtained by requiring all the decay particles to be found in the CDF silicon vertex detector (SVX). If we remove this constraint, we obtain additional signals as shown in the right plots, which are not used in this analysis due to the potential risk of introducing larger systematic errors. The ratio of efficiencies has been determined from Monte Carlo consisting of the NLO QCD b generator, the CLEO decay package[6], and the full detector simulation. The largest systematic arises from the uncertainty in the Λ_b polarization, $P(\Lambda_b)$. We observed the variation ($\sim 30\%$) for $P(\Lambda_b) = \pm 1$. Using the relative efficiency, the number of the observed events, $Br(\Lambda \rightarrow p\pi) = 0.639 \pm 0.005$, and $Br(K^0_s \rightarrow \pi^+\pi^-) = 0.686$ [2], we calculate the ratio of the product of the fragmentation fraction and the branching fractions as follows.

$$\frac{f_{\Lambda_b} Br(\Lambda_b \rightarrow J/\psi\Lambda)}{f_{B^0} Br(B^0 \rightarrow J/\psi K^0_s)} = 0.31 \pm 0.15 \pm 0.12 \tag{9}$$

Assuming that $f_{\Lambda_b}/f_d = 0.1/0.375$ and $Br(B^0 \rightarrow J/\psi K^0_s)$ [2] $= 3.7 \times 10^{-4}$, we have $Br(\Lambda_b \rightarrow J/\psi\Lambda) = (4.3 \pm 2.1 \pm 1.6) \times 10^{-3}$.

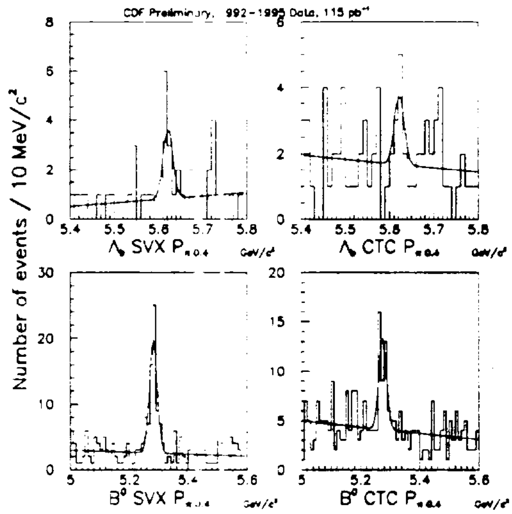

Figure 10: Invariant mass spectra for Λ_b and B^0

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